

A NEW TECHNIQUE FOR THE ON-ORBIT
CHARACTERIZATION OF CESIUM BEAM
TUBE PERFORMANCE

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ABSTRACT

A number of cesium beam tube atomic standards have exhibited a decreasing beam tube current with time. No test presently performed allows discrimination between the possible causes of this decrease. Also, no test presently performed measures tube signal-to-noise performance directly, accurately, and quickly. This paper describes such a test, which noninvasively measures the tube signal-to-noise performance, while possibly providing information to discriminate between causes of decreasing beam tube current. The technique characterizes cesium beam tube performance without measuring clock frequency stability. Consequently, no extensive analysis of long-term data is required.

INTRODUCTION

Clock performance is determined by the signal-to-noise ratio of the detected cesium (Cs) atomic resonance at 9.2 GHz. If this ratio degrades, the white-noise part of the Allan variance will degrade accordingly. The ratio is more dependent on the performance of the Cs ion detector (first dynode) than on the gain of the rest of the electron multiplier (Fig. 1) (succeeding dynode multiplication), unless the detector's secondary electron emission is severely degraded. Radically reduced emission from the detector is similar to reduced Cs beam flux and degrades the signal-to-noise ratio. With this new proposed measurement system we are studying the output-noise characteristics of the electron multiplier to determine whether it is possible to separate the loss of first-dynode emission from emission loss at successive dynodes. The loss of output signal by up to an order of magnitude has been observed, and is ascribed to multiplier degradation.

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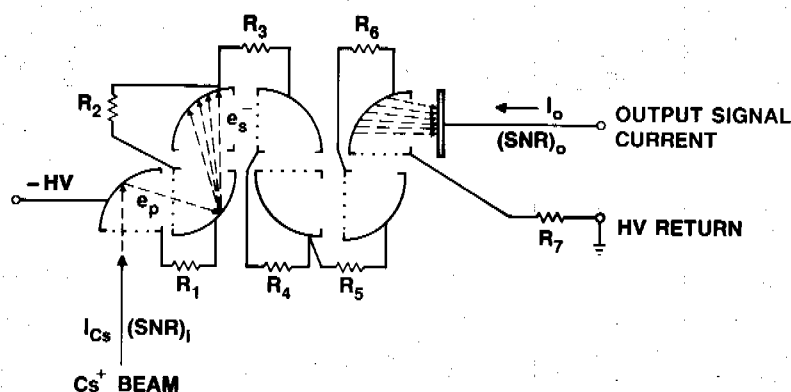


Figure 1. Cesium beam tube electron multiplier

DISCUSSION

For an average Cs ion current I_{Cs} into the first dynode of the electron multiplier in the Cs beam tube, the noise density $\phi_i(f)$ of the current will be given¹ by

$$\phi_i(f) = 2qI_{Cs} \text{ (W/Hz)} \quad (1)$$

where q = charge on an electron = 1.602×10^{-19} Coulomb. Then the signal-to-noise ratio for a 1-Hz noise bandwidth at the first-dynode input is

$$(SNR)_i = \frac{\text{signal power}}{\text{noise power/Hz}} = \frac{(\text{dc signal current})^2}{\phi_i(f)} = \frac{(I_{Cs})^2}{2q I_{Cs}} = \frac{I_{Cs}}{2q} \quad (2)$$

Depending on the conversion efficiency of the first dynode and the gain of the remaining dynodes, the output signal-to-noise ratio of the multiplier will be degraded by some factor that we shall call F . Then output signal-to-noise ratio for a 1-Hz noise bandwidth:

$$(SNR)_o = \frac{I_{Cs}}{2qF} \quad (3)$$

The conversion efficiency of the first dynode is expected² to be about unity, which will result in a degradation³, by a factor F of about two, of the signal-to-noise ratio at the output of the first dynode. The remaining

dynodes will have a much lesser effect. We therefore expect F to be slightly larger than two. If G and I_0 are respectively the gain of and the current out of the electron multiplier, we can write

$$I_0 = GI_{Cs} \quad (4)$$

Combining (3) and (4) gives

$$FG = \frac{I_0}{2q(SNR)_0} \quad (5)$$

Thus, from measurements of I_0 and $(SNR)_0$ we can calculate the factor FG . From the measurements of I_0 and $(SNR)_0$ and the calculation of FG , we can deduce a number of things. Perhaps most important, the measurement of $(SNR)_0$ sets the minimum value that the Allan variance of the clock can have for any given long integration time τ . ("Long" in this usage means that the clock loop gain is very high for frequencies on the order of $1/\tau$.) We can also make some distinctions between possible causes when I_0 , $(SNR)_0$, and FG change. For example, a graceful degradation of electron multiplier gain (i.e., where the gain of each stage degrades slightly) would result in I_0 and FG decreasing proportionately, with $(SNR)_0$ staying essentially constant. If the microwave power into the tube changed, the result would be a proportional change in I_0 and $(SNR)_0$, with FG staying constant. Here we are assuming that the initial power setting was for a maximum in I_0 . A change in the conversion efficiency of the first dynode of, say, from unity to one-half would result in I_0 approximately halving (although dark current would probably cause the change to be slightly less than one-half) and $(SNR)_0$ decreasing³ by a factor of approximately two to three.

MEASUREMENTS

A block diagram of our laboratory measurement system is shown in Figure 2. The noise bandwidth (NBW) of the 30-Hz bandpass filter was measured to be 7.23 Hz. The choice of the 30-Hz measurement frequency is arbitrary, since the noise density out of the tube is very constant with frequency as

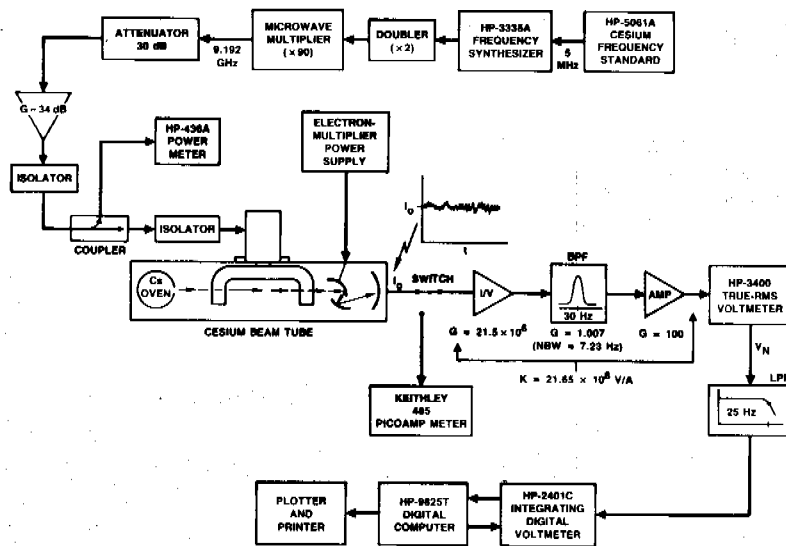


Figure 2. Block diagram of noise measurement system

predicted by Eq. (1). This is demonstrated in Figure 3. Figure 3a shows the noise output of the current-to-voltage (I/V) converter when it is terminated in an impedance approximately equal to the tube's output impedance. Figure 3b shows the noise output of the I/V converter when it is connected to the tube. The microwave power into the beam tube was adjusted for maximum current out of the tube. The tube used for the measurements was a commercial Cs beam tube. A Spectral Dynamic model SD301D spectrum analyzer was used for these measurements. From Figure 3b it is seen that the tube noise density is very flat; it is about 37 dB above the noise floor of the measurement system, and about 30 dB above the spectral spikes of the measurement system. The average current I_0 out of the tube is measured by connecting the tube directly to a Keithley model 485 picoammeter. Figure 4 shows the relationship between the input and output power spectral densities of the electron multiplier. The noise added at the output results from degradation in the gain of the electron multiplier, primarily at the first dynode. To measure this noise, a bandpass filter must be used to normalize the noise power per hertz.

To illustrate the usefulness of the system, two experiments were performed. In the first, the electron multiplier voltage was varied from -2000 V

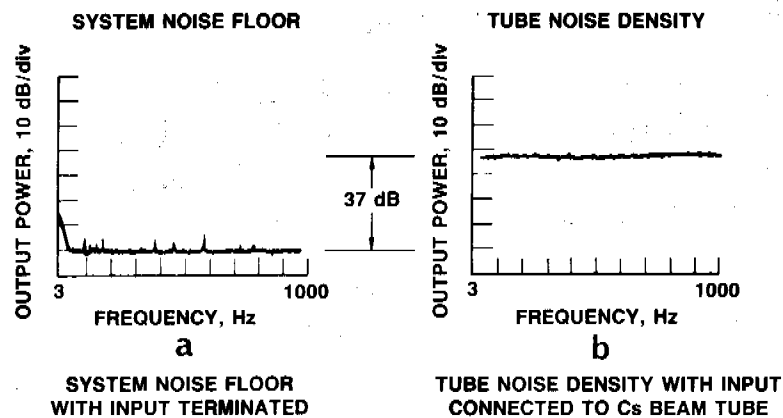


Figure 3. Power spectrum of current-to-voltage (I/V) converter output. (a) System noise floor. (b) Tube noise density.

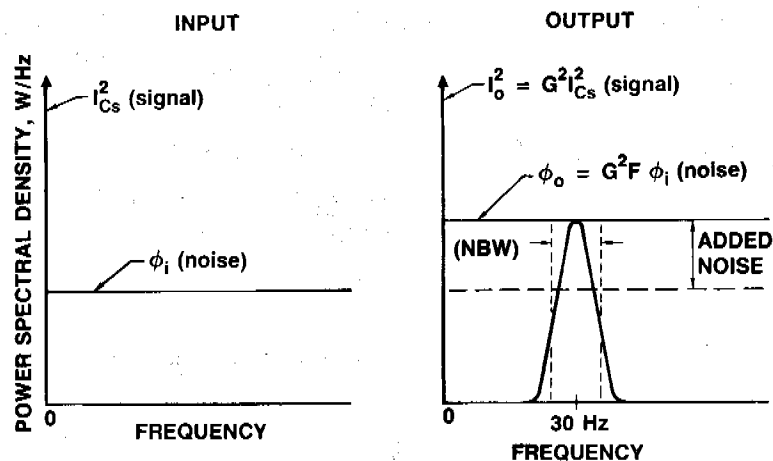


Figure 4. Power spectral density of electron multiplier

to -1375 V. Microwave power and tuning were adjusted for approximately maximum I_o for a multiplier voltage of -2000 V. In the second, the multiplier voltage was held constant at -2000 V and the microwave power level was varied from 0 to 152 μ W. The results are shown Figures 5 and 6. The current-to-voltage gain K from the tube output to the input of the HP 3400 true rms

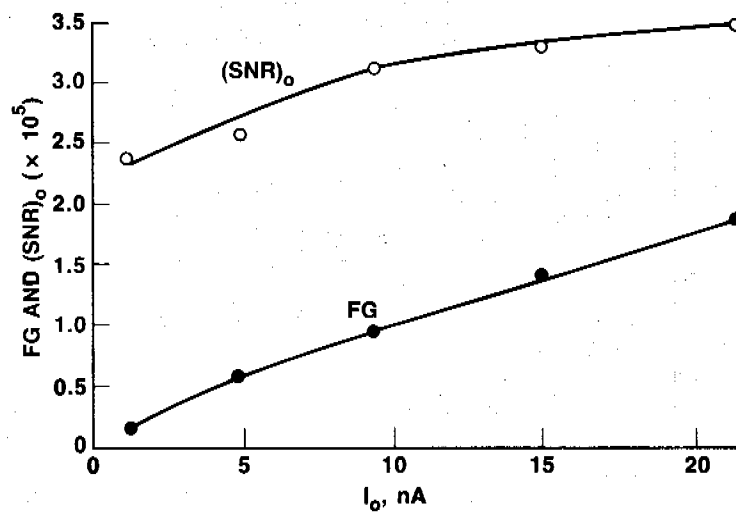


Figure 5. Relative gain and signal-to-noise ratio:
electron-multiplier voltage varied

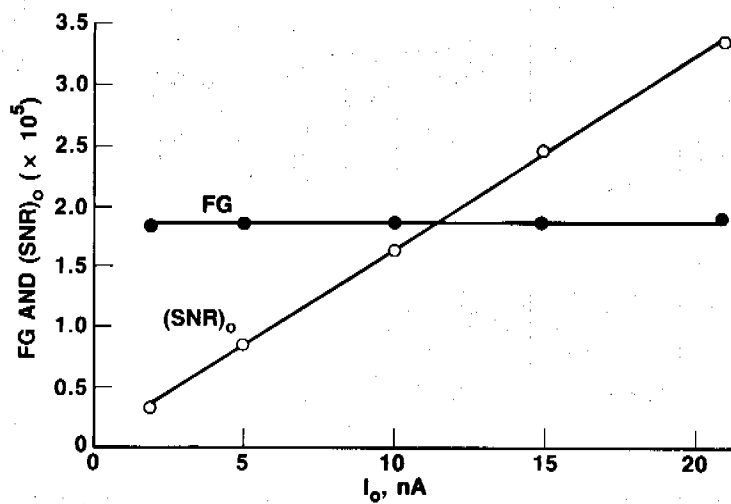


Figure 6. Relative gain and signal-to-noise ratio:
microwave power varied

voltmeter was measured to be $21.5 \times 10^8 \times 1.007 = 21.65 \times 10^8$ V/A. Using the measured noise bandwidth of the filter, the $(\text{SNR})_0$ is calculated to be

$$\begin{aligned} (\text{SNR})_0 &= \frac{\text{signal power}}{\text{noise power/Hz}} = \frac{(\text{dc signal current})^2}{(\text{noise current}/\sqrt{\text{NBW}})^2} \\ &= \frac{I_0^2}{(\bar{V}_N/21.65 \times 10^8)^2} \times 7.23 = 3.389 \times 10^{19} \left(\frac{I_0}{\bar{V}_N} \right)^2 \end{aligned} \quad (6)$$

FG can then be computed from Equation (5) to be

$$\text{FG} = \frac{1}{2 \times 1.602 \times 10^{-19} \times 3.389 \times 10^{19}} \times \frac{(\bar{V}_N)^2}{I_0} = 0.0921 \frac{(\bar{V}_N)^2}{I_0} \quad (7)$$

From Figure 5 we see that FG is nearly a linear function of I_0 , and that $(\text{SNR})_0$ decreases slightly as I_0 decreases. Both of these results are consistent with electron multiplier gain decreasing gracefully with decreasing voltage.

From Figure 6 we see that $(\text{SNR})_0$ decreases linearly with I_0 and that FG stays essentially constant. Both of these results are consistent with the conclusion that by varying the microwave power we are not changing electron multiplier performance (i.e., $\text{FG} = \text{constant}$), but are only affecting $(\text{SNR})_0$ as predicted by Equation (3).

A printout of a typical data output is shown in Table 1. The data set consists of 50 averages, each 10 sec long. Each average is printed out, along with the mean of the data set. A linear least-squares fit to the data set is computed, then the standard deviation about this fit is computed and printed out, along with the slope and Y-intercept of the fit. The standard deviation of the mean of the data set is calculated by dividing the standard deviation of the data set by the square root of the number of samples. Thus, for example, the standard deviation of the 0.3358-V mean in the data set would be $0.0123/\sqrt{50} = 1.47$ mV. To determine the noise floor of the measurement system,

a similar run was made with the I/V converter terminated in an impedance comparable to that for the beam tube output. With the HP 3400 scale set to 10 mV, the standard deviation of the data set was calculated to be 6.83 mV. This data set also consisted of 50 averages, each 10 sec long. The standard deviation of the mean would then be $6.83/\sqrt{50} = 0.966$ mV. The HP 3400 outputs 1 V for a full-scale reading, no matter what scale it is set on; this means, for example, that the measurement system noise for the 0.3358-V mean, which resulted from averages taken on the 300-mV scale, would be approximately $(300/10) \times (335.8/0.966) = 10,494$ times below the mean. In other words, this means that the noise floor is about 80 dB below this measurement. The worst noise-floor contribution for all of the data of Figures 4 and 5 occurred for the last point in Figure 4. For this point the noise floor was about $(30/10) \times (488.9/0.966) = 1518$ times below the mean. This equates to a noise floor about 64 dB below the measurement. In short, the data are negligibly limited by either noise in the signal itself or inherent in the measurement system.

Table 1. Measurement data of the electron multiplier's relative gain and output signal-to-noise ratio

V _N VALUES (taken with HP-3400 on 300-mV scale)					
-0.3297920	-0.3356450	-0.3129540	-0.3559810	-0.3387390	-0.3317080
-0.3462920	-0.3225170	-0.3421480	-0.3372390	-0.3423870	-0.3490170
-0.3268920	-0.3502590	-0.3549790	-0.3369340	-0.3359900	-0.3264090
-0.3385610	-0.3541650	-0.3443630	-0.3526960	-0.3500570	-0.3156610
-0.3259510	-0.3168740	-0.3419060	-0.3240740	-0.3483840	-0.3235480
-0.3225750	-0.3490520	-0.3224680	-0.3489750	-0.3265940	-0.3490910
-0.3487700	-0.3423870	-0.3348590	-0.3162830	-0.3160940	-0.3292870
-0.3290710	-0.3400840	-0.3512980	-0.3155360	-0.3290930	-0.3211600
-0.3410310	-0.3448130				
No. OF POINTS	= 50				
INTEG TIME (sec)	= 10.00000000				
MEAN	= -0.33581286				
STD DEVIATION	= 0.01233401				
SLOPE	= 0.00011999				
Y INTERCEPT	= -0.33887260				
FG	= 187304.88				
(SNR) ₀	= 83144.879				

How these measurements would be implemented in the on-orbit situation depends on the value of the available telemetry. If, for example, a wideband analog channel is available, the output of the I/V converter can be brought down directly and analyzed on the ground. If only very narrowband channels are available, the measurement of V_N must be made onboard. This requires a

filter such as the 30-Hz filter used herein, as well as a circuit to compute V_N . This is easily done with a true rms-to-dc converter such as an Analog Devices AD 636. Since I_0 is presently measured and telemetered down, the additional circuitry needed amounts to only a few chips and a handful of other components. We should also point out that if the I/V converter of a particular clock is narrow-banded, as is sometimes the case, it would have to be modified to pass the frequencies over which V_N is measured. This should present no technical problems.

SUMMARY

A simple test to determine the signal-to-noise performance of a frequency standard quickly, accurately and noninvasively has been described. This test also permits some degree of discrimination between several possible causes of performance degradation in frequency standards. A laboratory test setup was designed and constructed to examine the usefulness of the proposed test. The agreement between the test results and the analytical predictions was found to be excellent.

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